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P. D. Savage and M. L. Hines, *Ames Research Center, Moffett Field, California*
R. Barnes, *Lockheed Engineering and Sciences Company, Moffett Field, California*

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Ames Research Center
Moffett Field, California 94035-1000

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P. D. SAVAGE, M. L. HINES, AND R. BARNES*

Ames Research Center

Summary

The 14-day Spacelab Life Sciences 2 (SLS-2) mission became NASA's longest duration Shuttle mission when Columbia landed on November 1, 1993. The Spacelab carried a total of 48 laboratory rats housed in two research animal holding facilities (RAHFs) developed by the Space Life Sciences Payloads Office (SLSPO) at Ames Research Center. To properly maintain the health of these important research animals, sufficient quantities of food and water had to be available for the duration of the mission. An inflight refill unit (IRU) was developed by the SLSPO to replenish the animals' drinking water in flight, using the Shuttle potable water system in the middeck galley.

The IRU consists of two major subsystems, a fluid pumping unit (FPU) and a collapsible water reservoir (CWR). The FPU provides the system measurement and controls, pump, water lines, and plumbing necessary to collect water coming into the unit from the potable water system and pump it out and into the RAHF drinking water tanks. Connected to the FPU, the CWR is a KevlarTM reinforced storage bladder, which has a capacity of 6 liters in its expanded volume. This reservoir stores the water collected from the potable water system and facilitates its transport back to the Spacelab, where it is pumped into each of two RAHFs. Additional components of the IRU system include the inlet and outlet fluid hoses, a power cable for providing 28-volt direct current spacecraft electrical power to the pump within the FPU, a tether system for the unit when in use in Spacelab, and an adapter for mating the unit to the orbiter waste collection system in order to dump excess water after use in Spacelab.

This paper presents the design process and development approach for the Inflight Refill Unit, defines some of the key design issues which had to be addressed, and summarizes the inflight operational performance of the unit during the SLS-2 mission.

Introduction

The RAHF is a general use facility for housing rodents used in life sciences experiments conducted aboard SLS-2 (fig. 1).

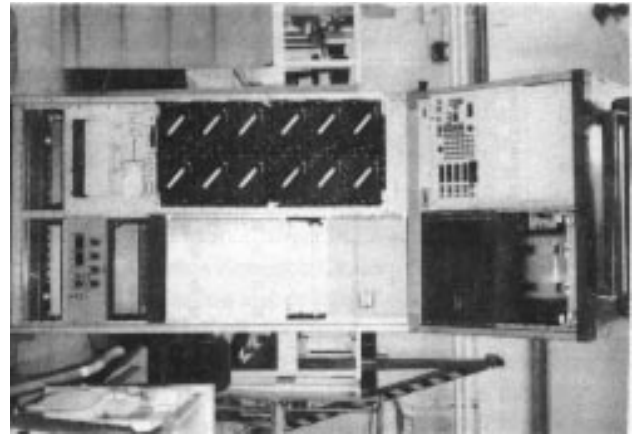


Figure 1. Rodent Research Animal Holding Facility.

The rodent RAHF system comprises seven basic subsystems: cage, cage module, environmental control system (ECS), water measurement and delivery, power, data, and control systems. A cage is divided by a mesh screen into two compartments, each of which houses one rodent. Each cage contains a waste management system plus individual feeders and watering fixtures. Twelve of these cages are contained in a cage module, which provides overall structural support, ducting for circulating air, lighting, drinking water plumbing, and temperature and humidity sensors. The environmental control system is mounted on the rear of the cage module and provides temperature- and humidity-controlled circulating air for the animals.

The water delivery system of the RAHF (fig. 2) stores nine and a half liters of water in a butyl rubber bladder pressurized with nitrogen to 55 psig within a water tank. This is enough water for 24 rodents for 10–11 days in space. The drinking water flows through a pressure regulator that maintains downstream pressure at 11 psig as the water flows toward the cages. Two manifolds downstream from the water tank are connected in parallel, each with 12 three-way solenoid valves. Each cage

*Lockheed Engineering and Sciences Company, Moffett Field, California.

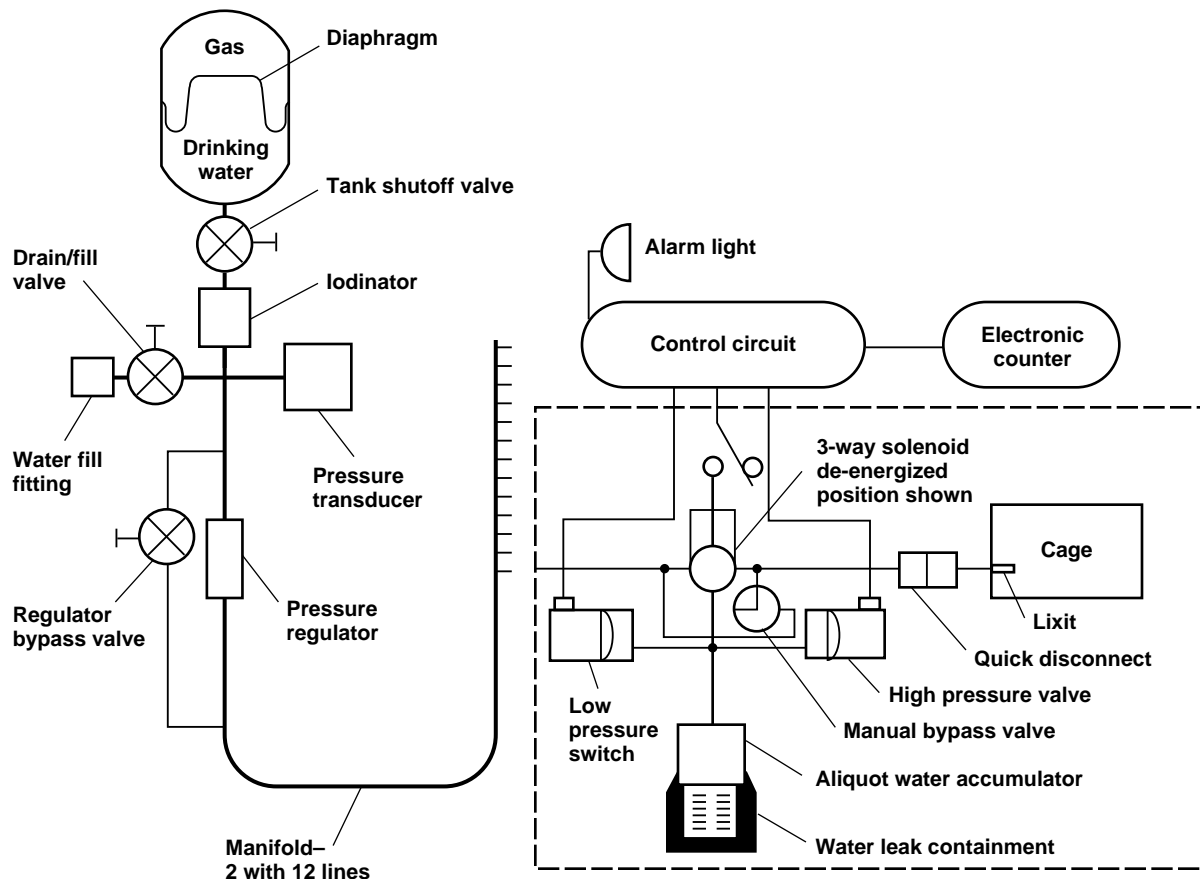


Figure 2. RAHF drinking water delivery system.

compartment is fitted with lixit valves that deliver water at 8 psig when the animal displaces an internal stem. Approximately 0.5 cc of water is delivered each time the lixit is actuated. The number of actuations and time of actuation are entered into the RAHF data acquisition system as a means of monitoring water utilization. In addition, a pressure transducer is located just downstream of the water tank and provides continuous monitoring of overall water system pressure and a means of determining residual water volume in the tank.

Background

The rodent RAHF has been flown aboard Spacelab three times. These flights were the 7-day Spacelab-3 mission in April 1985, the 9-day Spacelab Life Sciences-1 (SLS-1) mission in June 1991, and the 14-day SLS-2 mission in October 1993. The RAHF drinking water system design capacity was sufficient for the first two missions, but due to the 14-day duration of SLS-2, a method for supplementing the existing drinking water volume was required. This could be accomplished in one of two ways—either increase the capacity of the system through a design

upgrade or develop a standalone device which could add water obtained from a separate source to the drinking water system in flight.

The initial design approach was to modify the existing drinking water system to add a second water tank, thereby doubling the quantity of water available in flight. However, after assessing the impact of adding a second tank, i.e., maintaining structural integrity of the system, redesigning the plumbing, and the additional volume required within the Spacelab rack, it was determined that a standalone device would be developed instead. Such a device was chosen also for its capability to support future flights of other RAHF-type systems. In addition, a refill device had been successfully developed for the smaller animal enclosure module flown aboard SLS-1. This device, using a small peristaltic pump to transfer the water, did not have sufficient volume and pumping capacity to satisfy the requirements of the rodent RAHF for SLS-2, but did demonstrate that the concept of an inflight refill device was a viable one.

Inflight Refill Unit Design Requirements

The IRU design developed for SLS-2 was to be used to replenish water in each of two rodent RAHFs flown aboard Spacelab. When not in use, the unit would be stowed in one of several lockers mounted in Spacelab or the Orbiter middeck. Early in the design process, a detailed End Item Specification which defined key design requirements and performance criteria was prepared. These criteria are summarized below:

- Size and weight: the weight of the IRU (dry) will not exceed 33 pounds. The size of the IRU will be such that it can be stowed in a typical Spacelab locker with minimum internal dimensions of 17 in. wide × 14 in. high × 18 in. deep.
- Materials selection: all materials used in the design of the IRU will be compatible with the potable water provided by the middeck galley, with an iodine concentration of up to six parts per million. In addition, materials will be biocompatible with the flight animals as well as with all gasses and liquids used for cleaning, testing, and storage of the IRU.
- Water capacity: the IRU is to be capable of collecting and storing a total of 5–7 liters of water.
- Water flow rates: the IRU is to be capable of being filled with a minimum of 5 liters of water from the middeck galley potable water supply in less than 25 minutes. The system will also have a maximum outlet flow rate of 1.8 liters per minute. Protection devices will be included to prevent fill-water backflows from the IRU to the galley and from the RAHF water tank to the IRU.
- Mechanical, electrical, fluid interfaces: the IRU will be compatible with the Shuttle middeck galley potable water system, and will interface by means of the auxiliary port quick-disconnect (fig. 3). The IRU will be adaptable to mate with the Shuttle waste collection system to dump excess water following RAHF water tank filling. The IRU will also be compatible with the fill port quick-disconnect (QD) for the RAHF drinking water system. Finally, the IRU power cabling will be compatible with the mechanical and electrical characteristics of both the Shuttle middeck and Spacelab power supply systems.
- Acoustics: the IRU will not generate acoustic noise greater than 75 dbA as measured 1 ft from the noisiest surface.

- Human factors: the IRU will be capable of single crewperson operation and be designed to facilitate safe transport by a single crewperson from the Shuttle middeck through the Spacelab transfer tunnel and into the Spacelab.

- Astronaut crew safety: the integrity of the IRU will be water leak-tight to 110 percent of its maximum design pressure. The IRU design will also include a method for tethering to Spacelab structure to facilitate rapid safing and contingency egress operations.

- Reliability: the IRU will be zero-failure tolerant for water leakage and the water bladder will have a non-operating life of no less than two years, and a minimum useful life of three flights of 20 days each.

Inflight Refill Unit Design Process

The design of the IRU evolved through a development process common to spaceflight hardware developed by the SLSPO at Ames Research Center. The initial stages of requirement definition and design concept development culminated in a Preliminary Design Review (PDR), where key personnel within the Payloads Office were given the first opportunity to review the design approach for the IRU. During this phase remaining issues regarding design requirements were resolved and approval was given to continue the design development to the next phase, where a prototype was developed and a final design concept presented for review. Key design issues resolved during the PDR were the complexity of the bag design (balancing cost against the necessary structural complexity), ensuring sufficient flow rate, and minimizing pressure drop across the pump and plumbing.

The next phase of the design effort culminated in the Critical Design Review (CDR) for the IRU. The CDR also provided the first opportunity for astronaut crew input, as it was attended by a member of the SLS-2 flight crew. Key design issues addressed at the CDR included front panel controls, operational human factors, and back-contamination of the galley potable water supply. Following the CDR, the design concept for the IRU was baselined and approval was given to begin fabrication of three flight units. In addition, the prototype unit developed for the CDR was modified to reflect the final, baselined design configuration. This prototype unit was then used as an early training unit for the SLS-2 flight crew.

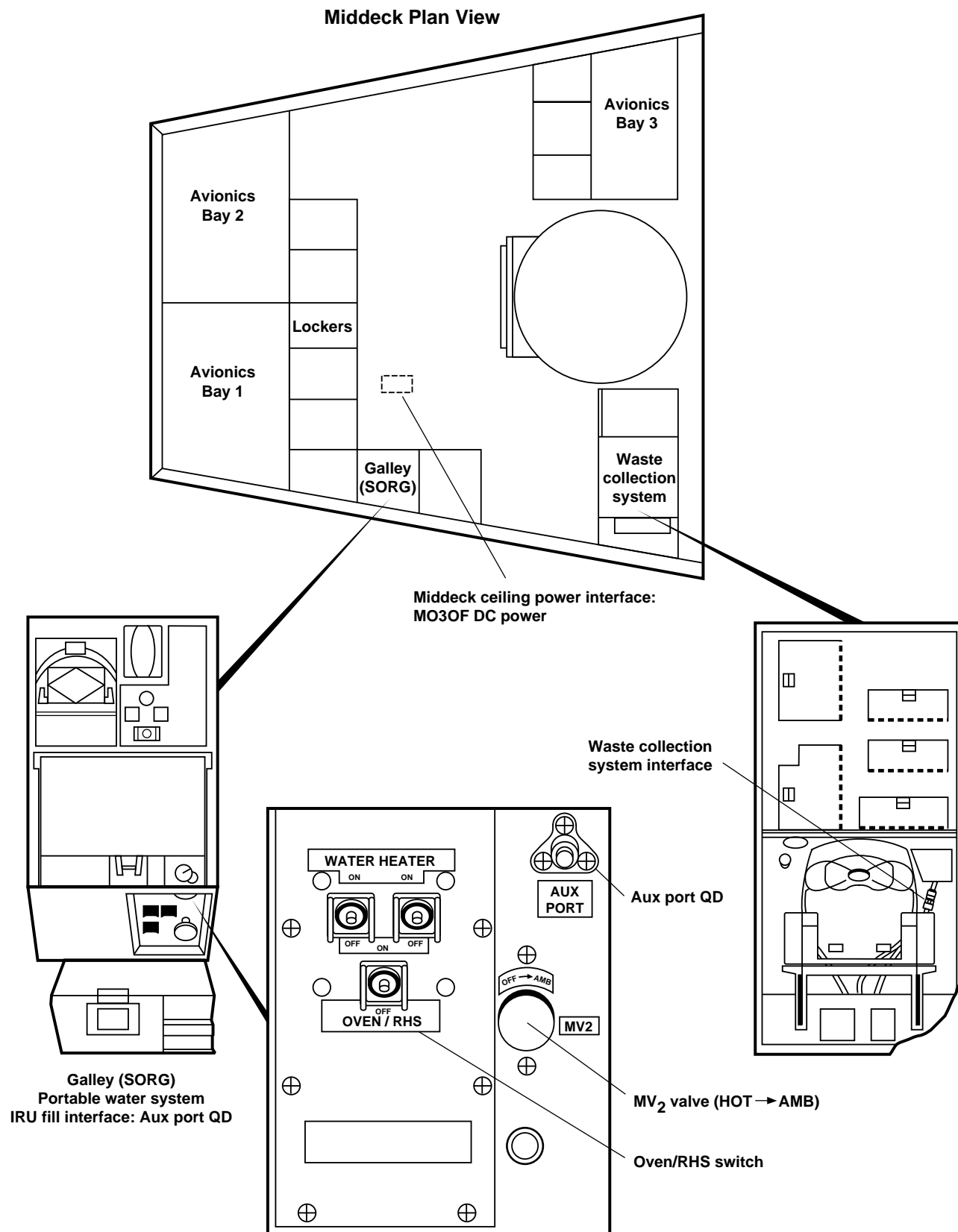


Figure 3. Inflight refill unit middeck interfaces.

Inflight Refill Unit Design Approach

The design of the IRU comprises two distinct and separate subsystems. An FPU houses the plumbing and pump necessary for collection of water from the middeck galley and filling of the RAHF drinking water tank in Spacelab. In addition, the FPU provides the various system controls and monitoring functions for crew operation inflight. The second IRU subsystem is a CWR that stores the water collected from the Orbiter middeck galley and allows for its transfer to Spacelab for filling the RAHF drinking water tank.

Fluid Pumping Unit

The FPU enclosure (fig. 4) is constructed from two aluminum Zero™ boxes mechanically fastened together and measures approximately 15 in. wide × 12 in. high × 10 in. deep. Within the FPU are a positive displacement pump containing an integral motor designed for continuous operation, associated tubing and valves for pumping the water through the system, and sensors and a printed circuit card for monitoring temperature and pressure within the system and controlling the function of the pump. On the exterior of the enclosure is a control panel that includes switches for applying power to the system and turning the pump on, gauges for displaying system pressure, and counters to measure the volume of water transferred to the RAHF drinking water tank.

Visual indications are provided for the operator as lamps for power on/off, pump on/off, completion of water tank filling, and conditions of over-pressurization and over-heating. Safety considerations also dictate the use of circuit breaker protection as well as protection against overheating of the pump motor, overpressurization of the water tank, and backflow of water into the middeck galley from the FPU or from the water tank into the FPU. In addition, a 2-micron filter is integrated into the plumbing system to help preclude back-contamination of the galley potable water supply.

Collapsible Water Reservoir

The CWR is a dual, rectangular, bellows-type bladder nominally designed to contain 6 liters of water when expanded to the maximum operational pressure of 20 psig at the middeck galley (fig. 5). It is attached to the back of the FPU through flexible tubing and a fluid quick-disconnect. The CWR is nominally constructed of two layers—an inner bladder of polyether polyurethane compatible with potable water, and an outer bladder of Kevlar-reinforced urethane which is resistant to punctures and maximizes protection from bursting due to over-pressurization. A stainless steel flange fitting is built into the top bellows, which is then attached to a thermoplastic hose with a double end, shut-off quick-disconnect at the other end. A stainless steel clamp is used at one corner of the lower bellows to close off a cleaning/drying port.

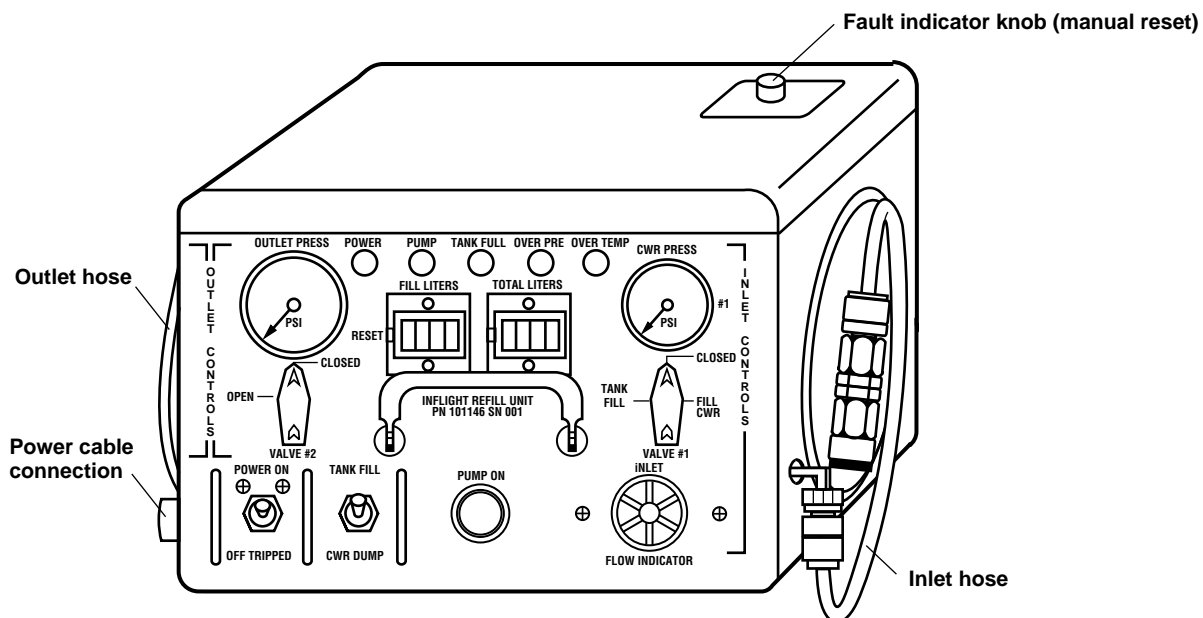
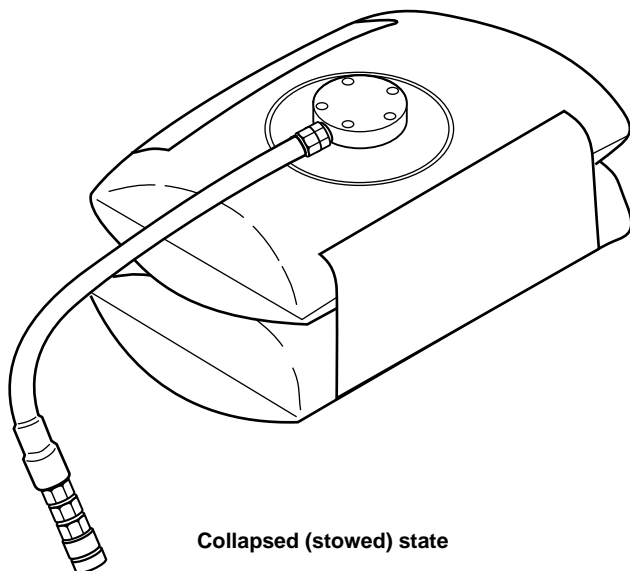


Figure 4. Fluid pumping unit.

Expanded state



Collapsed (stowed) state

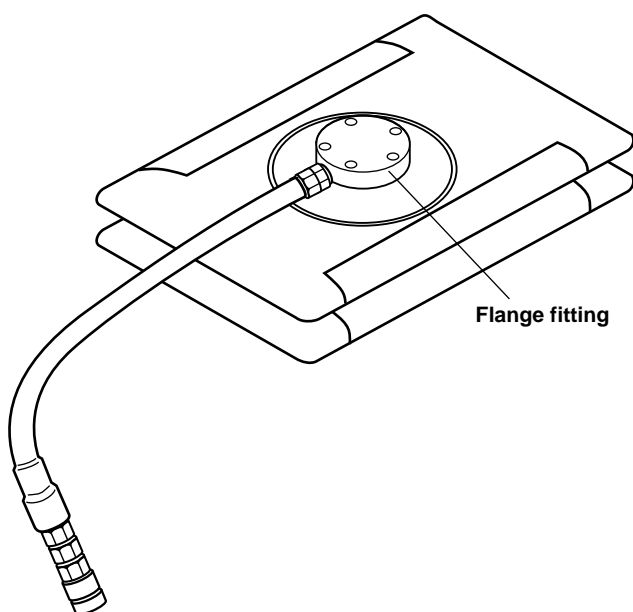


Figure 5. Collapsible water reservoir.

Supporting Elements

In addition to the two main IRU subsystems, several supporting components necessary for the function of the IRU in flight are flown. These include an inlet and an outlet fluid hose, an electrical power cable, and an adapter fitting for use in dumping excess water into the Orbiter middeck crew waste collection system. The inlet and outlet hoses are both 48-in. flexible stainless steel hoses that attach to the right and left-hand side of the FPU,

respectively. Each hose provides a quick-disconnect water line interface with either the middeck galley potable water supply (inlet) or the RAHF drinking water tank fill quick-disconnect (outlet).

In addition, a protective Nomex™ pouch which covers both the FPU enclosure and the CWR is attached with Velcro™, leaving the front FPU control panel accessible. The pouch can be positioned to accommodate either an empty (collapsed) or a filled (expanded) CWR.

Finally, to satisfy Shuttle crew rapid safing requirements, a tether system is flown which secures the IRU during use by strapping the system to the front face of the RAHF. The tether system is made of a Nomex webbing with carabiner snap hooks on each end. This would structurally secure the IRU in the event of an emergency egress by the crew.

Operational Overview

Since crewtime is at a premium during any Shuttle mission, operations must be streamlined and efficient. Considerable time and effort were invested in developing the procedures for crew operations associated with the IRU and then training the crew to ensure maximum proficiency. The nominal inflight operations associated with the IRU include filling of the CWR at the middeck galley potable water supply, transport of the system to Spacelab, and filling of the RAHF drinking water tank. IRU procedures are written for a single crewperson to perform. Contingency operations were also developed that included procedures for dumping excess water into the crew waste management system and troubleshooting malfunctions in the event of a failure of one or more IRU subsystems.

CWR Filling Operations

Filling of the IRU CWR begins by retrieving the IRU and the inlet hose from their respective Spacelab stowage locations and bringing them to the middeck. The inlet fluid hose is attached to the IRU FPU and then to the quick-disconnect at the auxiliary port of the galley potable water supply. Power is not required during this operation since the operating pressure of the galley potable water supply is sufficient to create flow. IRU valve #1 is placed in the FILL CWR position. Water flow into the CWR is verified by monitoring the Inlet Flow Indicator on the front panel of the FPU. After approximately 20 minutes, pressure in the CWR and the galley potable water supply will equilibrate at 12–20 psig. Flow will cease at this point, which is verified from the front panel flow

indicator. IRU valve #1 is then closed and fluid hose quick-disconnects are demated.

Transport to Spacelab

The filled IRU and associated outlet hose and power cable is transported to Spacelab by a single crewmember carrying the system by the handle on the front face of the FPU. Of course, maneuvering through the Spacelab transfer tunnel with the relative bulk of the filled IRU is made much easier in the microgravity environment of space, but care must be taken to ensure the exposed FPU control panel surface isn't impacted during the process.

RAHF Water Tank Filling Operations

Once the unit is in Spacelab, the outlet hose is connected to the RAHF drinking water tank fill port and the unit is tethered to the RAHF rack. The 28-V DC electrical power cable is connected between the FPU and the Spacelab rack Electrical Power Switching Panel (EPSP). The appropriate circuit breaker on the EPSP is switched on, the IRU power switch is also switched on, IRU valve #1 is placed in the TANK FILL position, and valve #2 is placed in the OPEN position. The volume counters are zeroed and the pump is then activated. Flow of water into the RAHF water tank is determined by observing the volume counters incrementing. Filling is completed when the TANK FULL indicator lamp is lit and the volume counters stop incrementing. Power is then switched off, hose and cable connections are demated, tether removed, and all equipment is restowed if both RAHFs have been filled, or the process is repeated if necessary (fig. 6).



Figure 6. RAHF drinking water system refill operations.

Contingency Operations

If water remains in the CWR following a RAHF water tank fill, the IRU is returned to the middeck and the outlet hose is connected to a waste collection system adapter. This adapter is then mated with the urine inlet connector at the waste collection system. Power is required for the FPU pump to dump the water, so the 28-VDC power cable is mated to an available Orbiter middeck power supply connector. The IRU and pump are then powered on and the excess water is dumped from the CWR at a rate of approximately 2 liters/min.

If a malfunction occurs in one or more of the IRU subsystems inflight, several procedures are available to the crew to troubleshoot the problem. Key malfunctions addressed include failure of the FPU pump, a leak in the CWR, and a failure to fill the RAHF water tank. A spare IRU is flown, as well as spare inlet and outlet hoses, in case the malfunction procedure does not correct the problem.

Inflight Performance on SLS-2

The IRU was used twice during the SLS-2 mission, once during preplanned timeline operations and once during an unplanned contingency top-off of the water tanks prior to landing. As planned, the first use occurred on flight day 7 of the mission, and included filling of the water tanks in both RAHFs. A total of 5.95 liters of water was added to the RAHF in rack 3 and a total of 5.35 liters was added to the RAHF in rack 7. All operations in the middeck during filling of the CWR were successfully completed. Filling of the CWR took approximately 15 minutes in both cases. The transport of the filled IRU back to the Spacelab also went smoothly. During the filling of the second RAHF tank, a problem was encountered in engaging the outlet hose QD with the water tank fill QD. This happened because, following the first RAHF fill, the outlet hose was left filled with water which created a hydraulic pressure head. Because of this pressure head in the hose, the QD could not mate with the water tank fill QD due to the poppet type of shut-off quick disconnect. This problem was quickly resolved when a crewmember was able to bleed off a small amount of water from the hose, relieving the pressure head and allowing the QDs to mate. Once this problem was resolved, the remainder of the RAHF fill operations were completed successfully.

The second use of the IRU occurred on flight day 13, when ground personnel determined that in order to support contingency mission extension scenarios, a final toff of both water tanks would be required prior to landing. This procedure was basically the same as that performed on flight day 7, with the exception that the CWR was filled once and the volume used to partially fill the RAHF water tank in racks 3 and 7. A total of 2.5 liters was added to the water tank in rack 3 and 3.28 liters was added to the water tank in rack 7.

Conclusion

The Inflight Refill Unit developed for the SLS-2 mission was proven to be an effective and reliable tool for inflight maintenance of animal drinking water supply, using the available Shuttle potable water system. The operations associated with its use minimized the crewtime required and could be performed by any available crewmember. The IRU now provides a flexible, reusable resource for future, extended duration missions that are flying animals in RAHF-type systems.

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